Generic modelling tools for the assessment of marine populations

by

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ABSTRACT. - In the New Zealand EEZ, most fish stocks are managed using TAC limits. Much of the scientific advice for the management of these stocks and associated species was derived from analyses using generic or standardised software packages and modelling techniques. These modelling techniques have also been applied to several Antarctic fish populations through various CCAMLR working groups, including the setting for TAC of toothfish fishery. CASAL is an age- (or size-) structured fish stock assessment model. Developed about ten years ago, it was mostly used in NZ EEZ stock assessments and in CCAMLR toothfish stock assessments. SeaBird is a population modelling package developed to undertake assessments of sea birds and help evaluate the impact of fisheries-related mortality on sea bird populations. The Spatial Population Model (SPM) is a spatially explicit integrated statistical catch-at-age stock assessment model that is similar in functionality aspects to CASAL. Implemented as a generalised package, it investigates the dynamics of more spatially complex populations, in particular, to test assumptions surrounding tag mixing in toothfish populations. All three models share similar design and structural characteristics: they generate integrated analyses, where there is flexibility in specifying the population dynamics, parameters, and model outputs; flexibility in the choice of observations; and are structured to allow easy interpretation of input and output files. Each of these models was designed to have a high level of documentation, quality assurance procedures, and scientific transparency to allow for robust peer review. The use of a documented, robust, and validated software tool in assessments, benefits both scientists and science managers. For scientists, it allows easy documentation of methods through the input and output files, improved efficiency in producing outputs, reduction of errors in underlying software code and its implementation, and easy transfer of methodology between scientists (regardless of stocks). For managers, benefits include greater efficiency in obtaining scientific advice, common methods used in assessments between stocks, and a standardised terminology. In addition to the standardised software packages, we also briefly describe two other modelling methods relevant to developing an ecosystem approach to fisheries: a parameter adjustment technique for mass-balance food-web models, and a boosted regression technique for developing relationships between species distributions and environmental conditions.

RÉSUMÉ. - Outils de modélisation générique pour l'évaluation des populations marines.

Dans les ZEE néo-zélandaises la plupart des stocks de poissons sont gérés avec des limites de TAC. Bien des avis scientifiques destinés à la gestion de ces stocks et des espèces concernées proviennent d'analyses utilisant des logiciels génériques et standardisés et des techniques de modélisation. Ces dernières ont été aussi appliquées à plusieurs populations de poissons antarctiques lors de divers groupes de travails de la CCAMLR, y compris pour l'établissement de niveau de capture admissible de pêcheries de légine. CASAL est un modèle d'évaluation de stock fondé sur la structure démographique (ou de taille). Développé il y a une dizaine d'années, il a été principalement utilisé dans l'évaluation des stocks de la ZEE néo-zélandaise et dans celle des stocks de légine de la CCAMLR. SeaBird est un logiciel de modélisation populationnel développé pour entreprendre des évaluations sur les oiseaux de mer et aider à mesurer l'impact de la mortalité issue de la pêche sur les populations de ces oiseaux de mer. Le modèle spatial populationnel (SPM) est un modèle d'évaluation de stock fondé sur une capture à un âge intégrée explicitement de manière spatiale, ce qui est équivalent pour les aspects fonctionnels à CASAL. Conçu comme un produit généralisé, il étudie la dynamique des populations particulièrement complexes au niveau spatial et en particulier teste les hypothèses entourant la dilution des marquages pour les populations de légine. Les trois modèles partagent une conception similaire et des caractéristiques structurales identiques: ils génèrent des analyses intégrées où il existe une flexibilité dans la spécification des dynamiques de population, des paramètres et des sorties du modèle; une flexibilité dans le choix des observations; et sont structurés pour permettre des interprétations aisées des classeurs d'entrée et de sortie. Chacun de ces modèles a été conçu pour posséder un niveau élevé de documentation, des procédures de garantie de qualité et une transparence scientifique pour permettre d'être compatible avec les exigences du système d'arbitrage des articles et des évaluations de quotas. L'utilisation d'un outil logiciel documenté, robuste et validé dans les évaluations, présente des avantages tant pour les scientifiques que pour les gestionnaires scientifiques. Pour les scientifiques il permet une documentation aisée des méthodes au travers des classeurs entrants et sortants, une efficacité améliorée dans la production des sorties, une réduction sensible des erreurs dans le codage lié au logiciel et dans sa mise en œuvre ainsi qu'un transfert aisé des méthodes entre scientifiques (sans tenir compte du stock). Pour les gestionnaires les bénéfices comprennent une efficacité améliorée dans l'obtention d'un avis scientifique, des méthodes communes utilisées dans l'évaluation des stocks et une terminologie plus standardisée. En plus des offres de logiciels standardisés nous décrivons aussi deux autres méthodes de modélisation relatives au développement de l'approche écosystémique des pêcheries: une technique d'ajustement de paramètre pour les modèles fondés sur l'utilisation des réseaux trophiques ajustés sur la biomasse et une technique de régression forcée pour comprendre les relations entre la distribution des espèces et les conditions environnementales.

Key words. - Integrated analyses - Population models - Bayesian - Stock - Software - Fisheries.

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New Zealand (NZ) has the fourth largest Exclusive Economic Zone (EEZ) in the world at 4.4 million km^2. This area encompasses sub-tropical to sub-Antarctic waters, 16 000 marine species, and 130 commercially-exploited fish species. Of the commercially-exploited fish species, 96 are managed through a Quota Management System (QMS), with total allowable catch (TAC) limits (source NZ Ministry of Fisheries, www.fish.govt.nz).

The management of these stocks is administered by the New Zealand Ministry of Fisheries under *The 1996 Fisheries Act*. One of the requirements of the New Zealand fisheries legislation is that stocks are to be managed at or above the biomass corresponding to the maximum sustainable yield (B_{MSY}). Outside the New Zealand EEZ, international fisheries obligations such as those dictated by the Commission of the Conservation of Antarctic Marine Living Resources (CCAMLR) or the Commission for the Conservation of the Southern Bluefin Tuna (CCSBT) are also administered in the New Zealand Ministry of Fisheries.

Current management requires regular stock assessments to be carried out on the most valuable fisheries, which represent about 66% of the total NZ EEZ catch in weight. But New Zealand has limited scientific resources to dedicate to fish stock assessments requirements, both in terms of fisheries research funds and fisheries modellers. As a result, the National Institute of Water and Atmospheric Research (NIWA) has been developing a range of standardised modelling tools. These allow the capture of experienced modellers' knowledge into the software, the fast training of new people through detailed manuals and standard code, and the easy replication or update of existing stock assessments.

New Zealand is also following the international trend to consider fisheries within an ecosystem context. Two modelling methods (a parameter adjustment technique for mass-balance food-web models, and a boosted regression technique for developing relationships between species distributions and environmental conditions) are being used to develop awareness of how ecosystem changes can affect fish, and how the effects of fishing on marine ecosystems can be mitigated or managed as mandated by the New Zealand fisheries legislation.

As part of its international fisheries obligations, New Zealand provides scientific support to CCAMLR, in particular through its participation to CCAMLR's Working Group on Statistics Assessments and Methods (WG-SAM), and Working Group on Fisheries Stock Assessment (WG-FSA). The modelling tools developed by New Zealand are used by CCAMLR, with the statistical fish stock assessment software tool called the C^{++} algorithmic stock assessment laboratory (CASAL), being endorsed by CCAMLR and used for most of its toothfish (*Dissostichus* spp.) stock assessments. Toothfish is a finfish species of high ecological and economical importance around the Subantarctic and Antarctic seas, including the Kerguelen plateau where TAC in the French EEZ in 2008 was 6 000 t (www.taaf.fr). The other modelling techniques discussed below have also been used in the Antarctic context and presented at various CCAMLR meetings, and could be of interest to scientists working on the Kerguelen plateau.

METHODS

Standardised population models

The three standardised population models used were: CASAL, SeaBird and Spatial Population Model (SPM). CASAL is a size- or age-structured statistical fish stock assessment software tool. It was developed about 10 years ago and is used for most NZ EEZ stock assessments (e.g., Ministry of Fisheries Science Group, 2009). It has been used at CCAMLR since 2005 for Antarctic toothfish (*Dissostichus mawsoni,* Norman 1937) stock assessments (Dunn and Hanchet, 2009; SC-CCAMLR-XXIV, 2004).

SeaBird was developed to undertake the statistical assessments of sea bird populations and to assist in evaluating the impacts of fisheries on seabird populations. It is currently being used to assess the populations such as Bullers albatross (*Thalassarche bulleri,* Rothschild 1893), white capped albatross (*Thalassarche steadi*, Falla 1933), and the New Zealand black petrel (*Procellaria parkinsoni,* Gray 1862) around New Zealand (e.g., Francis *et al.,* 2008).

The SPM is a spatially explicit integrated statistical catch-at-age stock assessment tool. While still in development, it is being used to investigate assessment biases from alternative mixing assumptions of tags in the Ross Sea toothfish assessment (Dunn and Rasmussen, 2009; Dunn *et al.,* 2009).

These three tools share common general principles. They integrate parameter estimation within population modelling. They are designed for flexibility: provide the ability to implement a range of alternative model structures; the user can choose the number and sequence of events in a model year; the data used can be from many different sources of information, for example catch-at-age or catch-at-size data from commercial fishing, survey and other biomass indices, survey catch-at-age or catch-at-size data, and tag-release and tag-recapture data; and to derive explicit estimates of uncertainty, estimation is used either by maximum likelihood or Bayes. By generating point estimates of the parameters of interest, these tools can also calculate likelihood or posterior profiles and can generate Bayesian posterior distributions using Monte Carlo Markov Chain methods. All three modelling tools can also be used as simulation platforms.

Central to the design of these modelling tools is the concept of integrated analyses. Integrated analyses are those that integrate a range of appropriate data as observations within the model to inform parameter estimates. For example, the use of catch-at-age or -length data in a fisheries model can

be combined with absolute or relative abundance information (e.g., survey estimates or tag recapture data), and movement and maturity observations to inform a range of model parameters.

CASAL (Bull *et al*., 2008) is specifically designed for fish stock assessments. It can be used for a single stock for a single fishery, or for multiple stocks, areas, and/or fishing methods. This structure can be used to implement a variety of population models, with intermingling of stocks, areal migrations, and multiple fisheries that use different fishing methods and cover different areas and times. CASAL can implement both age-based and size-based models, and can approximate simple age-size models using 'growth-paths'.

SeaBird is a generalised age- or stage-structured seabird population dynamics model. Like CASAL, SeaBird can combine parameter estimation with a range of alternative population dynamics, which is rare in the seabird modelling literature (Arnold *et al.,* 2006; White and Burnham, 1999). SeaBird allows for a more flexible (i.e., less-structured) partition than in CASAL, for example a split between non breeders, successful breeders and failed breeders. Other differences include the use of user-defined parameters, parameter mapping to reduce the numbers of parameters if some are expected identical, and individual-based mark recapture computations.

The SPM (Dunn and Rasmussen 2009) is a generalised spatially explicit age-structured population dynamics and movement model. The population structure follows the usual population modelling conventions and is similar to that implemented in CASAL, but within an arbitrary shaped spatial structure. Movement is parameterised by movements that are functions of known attributes at each spatial location.

Ecosystem modelling tools

Species in marine ecosystems are connected in many ways, but one of the most fundamental types of links between species is trophic, that is, the feeding of one organism on another. Whole ecosystem or end-to-end models aim to quantitatively represent a simplification of an entire food-web in order to explore the dynamics of the relationships between species. The most widely used marine food-web model is Ecopath (e.g., Christensen and Walters, 2004). Ecopath has many failings, and one of the most significant is the lack of rigour in the adjustment of an initial set of parameters to a set which are internally consistent or 'balanced'. A balanced model is one in which material and energy flows through the ecosystem and is appropriately accounted for. At NIWA, we have developed a novel method that takes an initial set of parameters for an Ecopath-type model (biomasses of organisms present, their energetic rates, and the trophic links between species) and adjusts them simultaneously and objectively to give a balanced model taking into account estimates of relative uncertainty between parameters and appropriately handling the large range of magnitude (typically > 6 orders of magnitude) in trophic flows between groups. This method was used to develop a balanced end-to-end food web model for the Ross Sea to investigate potential ecosystem effects of fishing for Antarctic toothfish (Pinkerton *et al*., 2010a).

Mapping the distribution of species is an important step toward elucidating their role in ocean ecosystems. Recent years have seen rapid advances in the use of multivariate statistical methods to relate sparse measurements of species abundance to environmental characteristics in order to investigate patterns of occurrence over large spatial scales (10^3-10^5 km) and over extended periods (months to decades) (Elith *et al.,* 2007; Guisan and Zimmerman, 2000). One particular multivariate statistical technique called boosted regression trees (BRT; Leathwick *et al*., 2006) shows particular promise in linking *in situ* measurements of species presence and relative abundance to long-term averages of physico-chemical environmental conditions. In New Zealand, we have applied BRT to map large scale distributions of key zooplankton (Pinkerton *et al*., 2010b) and fish species (Mormede *et al*., 2010). This technique has applications to investigating overlap between species for evaluating the potential for interactions and in assessing the conservation value of spatially managed areas.

RESULTS

This section presents illustrative examples of use for each of the population modelling tools discussed.

CASAL - Assessment of hoki (*Macruronus novaezelandiae,* Hector 1871) in New Zealand (Ministry of Fisheries Science Group 2009)

The New Zealand hoki fishery is one of the most commercially valuable fisheries in New Zealand and a large volume of fisheries-independent information is available. It has a complex stock structure, comprised of two intermixing stocks in four locations around New Zealand. The New Zealand hoki fishery received Marine Stewardship Council Certification in 2001 and was recertified in 2007.

Hoki are widely distributed throughout New Zealand waters from 34°S to 54°S, with greatest abundance at depths between 200 and 600 m. They mature at about 3 to 5 years old, between 60 and 70 cm total length. The assessment model partitioned the population into two sexes, 17 age groups (1 to 17), two stocks (East and West), and four areas (Chatham Rise, West Coast South Island, Sub-Antarctic and Cook Strait). While the adult fish of the two stocks do not mix (those from the West stock spawn in the West Coast and spend the rest of the year in the Sub-Antarctic and the East stock fish spawn in Cook Strait and spend the rest of the year

on the Chatham Rise), juvenile fish from both stocks live on the Chatham Rise.

Five series of abundance indices were used in the assessment: a winter acoustic survey series of West Coast South Island (8 years), a December trawl survey of Sub-Antarctic (12 years), an April trawl survey of Sub-Antarctic (3 years), a trawl survey of the Chatham Rise (18 years), and an acoustic survey of Cook Strait (15 years). Catch at age data were used for all fisheries (through observer coverage of the fishery).

Two alternative runs were carried out in the 2009 assessment, Bayesian posterior distributions were estimated for each using a Markov Chain Monte Carlo approach (Fig. 1). Five-year projections were also carried out under two alternative assumptions about future recruitment (Fig. 2). These models made the basis for recommendations of future total allowable catch for hoki in New Zealand.

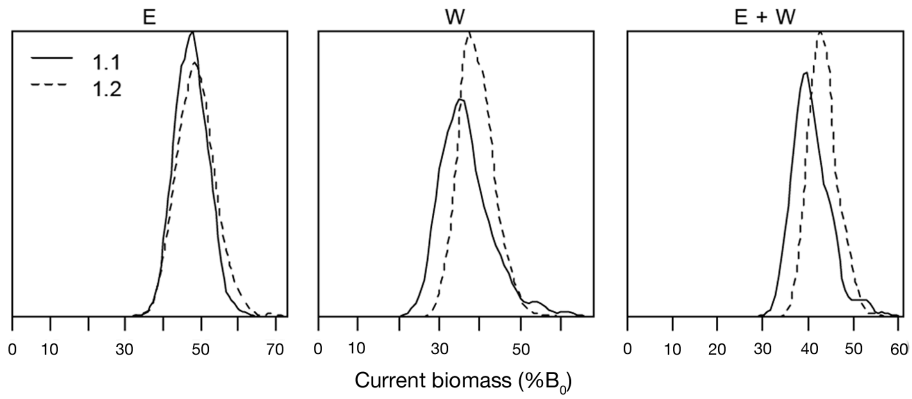

Figure 1. - Estimated posterior distributions of current (spawning) biomass ($B_{2008\text{-}09}$) of hoki (*Macruronus novaezelandiae*), expressed as $\%B_0$ for the East (left panel), West (middle panel) and East plus West stocks (right panel) from the final model runs. Reproduction of Figure 3 of the report (Ministry of Fisheries Science Group 2009).

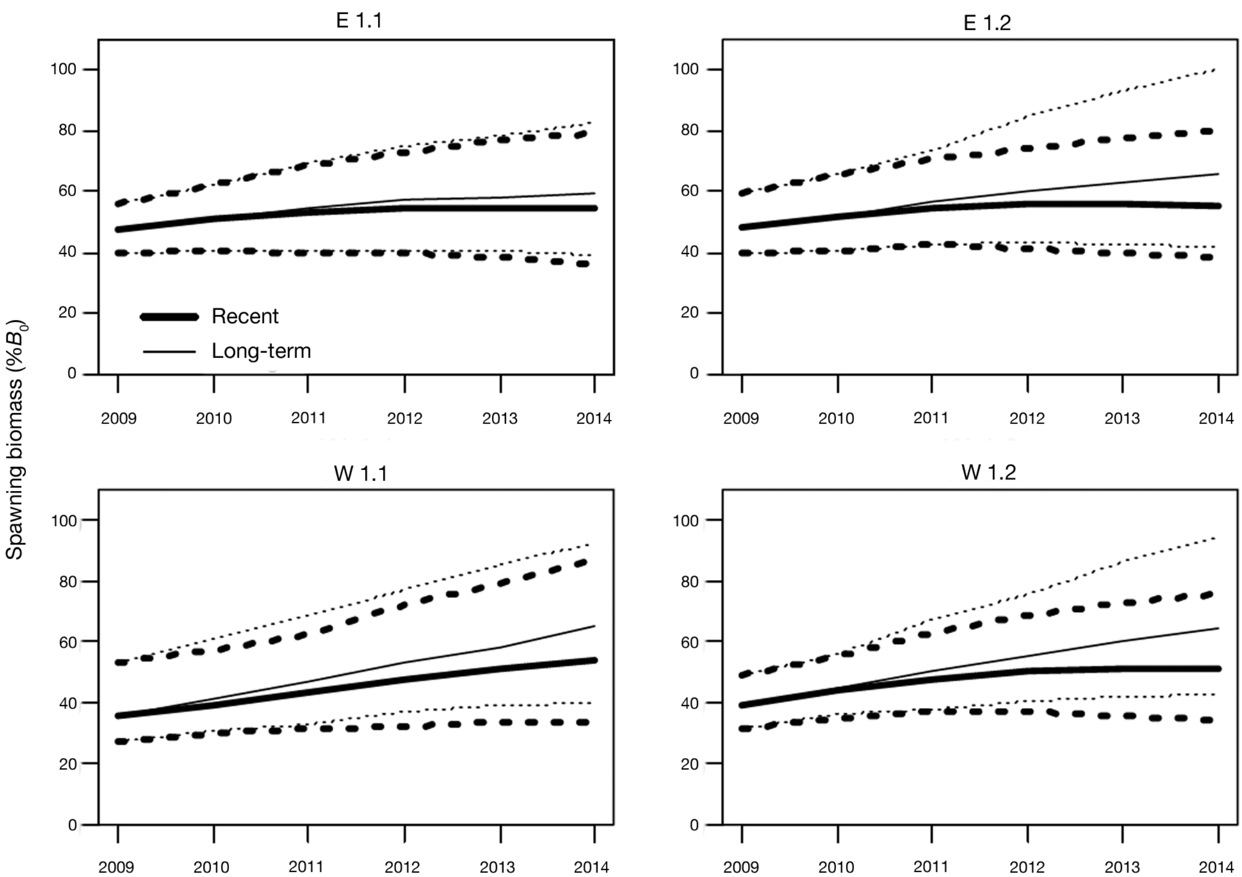

Figure 2. - Projected spawning biomass (as $\%B_0$) of hoki (*Macruronus novaezelandiae*) assuming long-term (thin lines) or recent (thick lines) recruitment: median (solid lines) and 95% confidence intervals (broken lines). Reproduction of Figure 5 of the report (Ministry of Fisheries Science Group 2009).

SPM - Model of Antarctic toothfish (*Dissostichus mawsoni,* Norman 1937) in the Ross Sea Region of Antarctica (Dunn *et al.,* 2009)

Antarctic toothfish in the Ross Sea Region is currently being assessed using a single stock model implemented in CASAL (Dunn and Hanchet, 2009), but a concern is that the mixing assumptions for the tag data may not be valid, and the assessment may be biased.

Operating models with patterns of movement based on the ontogenic lifecycle of Hanchet *et al*. (2008) were implemented in SPM. Two sets of spatial resolutions were assumed for the Ross Sea Region: a 6x10 grid (coarse-scale) or a 17x25 grid (fine-scale). Spatial distribution and movement parameters were estimated using spatially-explicit observations of proportions-at-age of the commercial catch, proportions-at-age of tag-released fish, proportions spawning, and proportions of scanned fish recaptured with a tag.

Examples of estimates of population abundance are detailed in figure 3. Further work is required to develop the operating models to a point where they can be used for carrying out useful simulation work to address uncertainties within the assessment models.

SeaBird - Progress with SeaBird modelling of New Zealand black petrel (*Procellaria parkinsoni,* Gray 1862) on Little Barrier Island (Francis and Bell, 2009)

The New Zealand black petrel is a medium-sized endemic seabird that was once found on most North Island ranges over 400 m, but is now limited to two known current breeding locations on Little Barrier Island and Great Barrier Island. Black petrels nest in burrows, usually above 400 m in altitude, and within 50 m either side of ridge lines. This species is rated as 'vulnerable' by the International Union for Conservation of Nature (IUCN). Total population on both breeding sites is estimated at 550-1 100 breeding pairs.

Juvenile birds were categorised as years 1 to 9. Adults were split between pre-breeders, non-breeders, failed-breeders and successful breeders. Banded birds were individually followed through the model. Three types of data are available: fisheries bycatch data from observers, mark recapture data and abundance estimates. Bycatch data was not used in the modelling due to the lack of information, a combination of low fisheries observer coverage and low bycatch numbers. Mark recapture data was available since 1995, two or three times a year. Formal abundance estimates were obtained since 1989.

Population and parameter estimates were carried out within the model in a single step, which is unusual for seabird data analysis. Estimated age-at-first breeding is showed in figure 4.

DISCUSSION

Due to limited resources in fisheries modelling in New Zealand, NIWA has developed documented, robust, and validated software tools for fish and seabird population assessments, and spatially-explicit fish population modelling. These tools have shifted resource use away from coding and building of models to scientific investigation of plausible models. They have allowed the capture of experienced scientists' knowledge in the software, easy training of staff to run population models without the need for specialised high end programming/coding knowledge, and easy replication

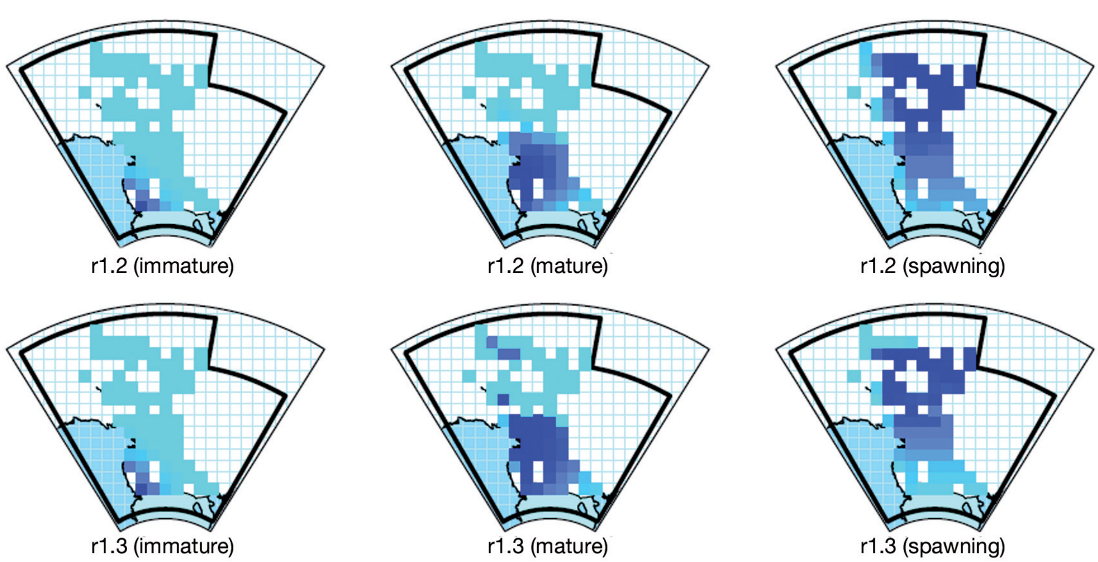

Figure 3. - Estimates of population abundance at the beginning of the 1995 year for (left) immature, (middle) mature and (right) spawning Antarctic toothfish (*Dissostichus mawsoni*) for the fine-scale restricted area model runs 1.2 and 1.3. Reproduction of Figure A3-3 of Dunn *et al*. (2009).

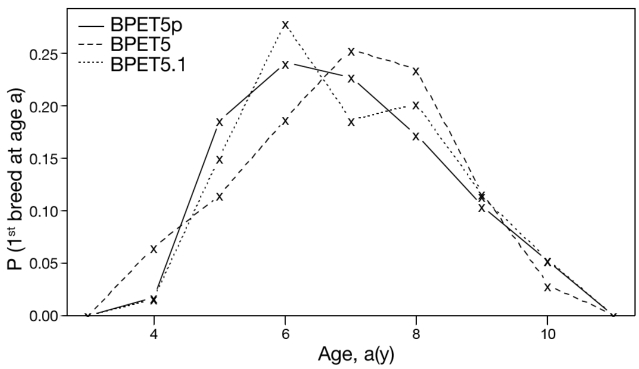

Figure 4. - Comparison of estimates of age at first breeding of New Zealand black petrel (*Procellaria parkinsoni*), as determined by three different models. Reproduction of Figure 15 of Francis and Bell (2009).

or update of older work.

These tools provide benefits to both scientists and managers. To scientists, they allow easy documentation of methods through the input and output files, improved efficiency in producing outputs, reduction of errors in code and implementation, easy peer review of models, and easy transfer of methods between different stocks. To managers, benefits include greater efficiency in obtaining outputs, common methods used in assessments between stocks, and a more standardised terminology.

Although the tools described above are suitable to more current fish stocks, changes in technology and management requirements over the last decade require new tools to be developed. Future work by NIWA includes the development of the next generation of fisheries population model (FPM), through open collaboration with open source code. Advances in terms of technology mean better management of memory and faster computational speeds can now be achieved, with the potential to interface with other programmes such as R, Perl or Python. Changes in fisheries management requirement call for improved flexibility in model structures, including time-varying trends in parameters and more flexible observation types. FPM is also intended as a platform for Management Strategy Evaluation, which current tools cannot achieve due to computational times.

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